Indian J. Phys. **75B (2)**, 105–108 (2001)

I J P B
— an international journal

Beam-foil studies on aluminum

Aparna Shastri, Saraswathy Padmanabhan, B N Rajasekhar, P Meenakshi Raja Rao*, C A Desai† and M B Kurup†
Spectroscopy Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400 085, India
†Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai-400 005, India
E-mail pmrr@apsara barc ernet in

Received 7 September 2000, accepted 22 January 2001

Abstract The beam-foil spectrum of aluminum was recorded in the wavelength region of 3400–4700 Å, using Al^+ beam of energy 296 KeV Several lines belonging to Al II, Al III and Al IV were observed Lifetime measurements and excitation function studies were carried out on some of the intense lines observed Mean lifetime of the lines at 4663 Å (Al II) and 3492 Å (Al IV) are being reported for the first time

Keywords Beam-foil spectroscopy, lifetime, excitation function

PACS Nos. 32 70 Cs, 34 50 Fa

1. Introduction

Beam-foil spectroscopy is a very sensitive technique for studying the lifetimes of excited states of atoms and ions. Due to the non-selective nature of the beam-foil excitation, a large number of charge states and excited levels which are not easily accessible by conventional excitation processes are populated copiously. Excitation function studies give valuable information about the charge state of the emitting species as well as the nature of interactions within the foil.

The beam foil spectrum of aluminum has been studied previously by several authors. In the low energy region of 400 KeV, spectra as well as lifetimes have been studied for Al I to Al III [1–4]. A more extensive study was carried out by Weckström and Nystén [5] at 720 KeV. They were able to observe lines belonging to Al I–Al VI in the wavelength region of 1800 Å to 7000 Å. Several excitation function studies and lifetime determinations were also carried out by them However, for many of the lines, only a single lifetime determination exists, often with large experimental errors. For some of the spectral lines, there were discrepancies in the assignment of the emitting species *e g*. 4654 Å, which was listed as belonging to Al IV by Weckström *et al* [5] and as belonging to Al II by Kaufman *et al* [6].

Keeping in view the important contribution of accurate data to a better understanding of the spectra, it was found worthwhile to reinvestigate the excitation functions and lifetimes of some of the spectral lines in the region 3400 Å to 4700 Å.

2. Experimental setup

The experiments were carried out using singly ionized aluminum beams from the 400 KeV accelerator at the Tata Institute of Fundamental Research. The ions are produced in a Nielson-type hot cathode ion source using $AlCl_3$ as the charge material and CCl_4 as the carrier gas. The positive ions produced in the ion source are extracted using an extraction voltage and then focussed axially by an Einzel lens and mass analyzed by an analyzing magnet. A mass analyzed Al^+ beam is accelerated and then focussed by a quadrupole lens before entering the target chamber. The target chamber is basically a stainless steel cross of 100 mm diameter containing the target holder assembly. It is evacuated to a pressure of 1×10^{-6} mbar using a cryo pump to give hydrocarbon free vacuum. The target holder is a stainless steel rod with a target ladder capable of holding up to 10 carbon foils at a time. In case of foil rupture during the experiment, one can change the foil under vacuum without disturbing the other experimental conditions. The target holder can be moved vertically in order to select the foil as well as traversed horizontally by a maximum distance of 75 mm. The isotopically pure Al^+ beam of energy 296 KeV is then made

* Corresponding Author

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to pass through Carbon foils of thickness between 6–8 μg/cm^2. Due to the beam-foil interaction, the ions get further ionized and excited. The emerging beam consists of highly excited ions in various charge states, which copiously emit photons. The emitted optical radiation is detected perpendicular to the beam axis, downstream of the foil using a 0.45 m Czerny Turner monochromator coupled to a photon counting system. The detector used is a Peltier cooled photomultiplier. Lifetime measurements are carried out by recording the relative intensity normalized to a fixed amount of charge collected by a Faraday cup at several positions of the foil along the beam axis. For excitation function measurements, the intensities normalised to a fixed amount of charge collected by the Faraday cup, were recorded at various energies for a fixed foil position. In all these cases, the time taken for collecting data was monitored and background correction was applied. The experimental procedure has been described in greater detail elsewhere [7].

3. Results and discussion

In the present studies, the beam-foil spectrum of aluminum was reinvestigated in the wavelength region of 3400 Å–4700 Å. The spectra consisted of lines belonging to charge states Al II, Al III and Al IV. No line belonging to Al I was observed in this region. A part of the recorded spectrum in the region 4400 Å to 4700 Å is shown in Figure 1.

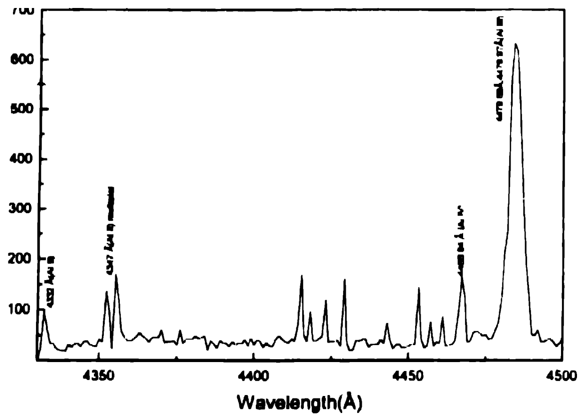

Figure 1. Beam-foil spectrum of aluminum (4330 Å to 4500 Å)

The spectral lines observed with good intensity are listed in Table 1. The identification and assignment of lines were based on the compilation by Kaufman and Martin [6]. Seven of the intense lines *viz.* 4663 Å (Al II), 3601 Å, 4479 Å, 4512 Å, 4529 Å (Al III) and 3492 Å, 4654 Å (Al IV) which were found to be free from line blending were chosen for lifetime and excitation function studies.

3.1. *Mean lifetime measurements :*

Mean lifetime measurements were carried out using the procedure of measuring the intensity decay of a line for constant beam charge as a function of distance from the foil. Single and multiple exponential fitting programs were used to extract the lifetimes from the measured decay curves

Table 1. List of intense lines observed

Wavelength (Å)	Species	Transitions
3492.23	Al IV	$2s^2 2p^5(^2P^0_{3/2})4p^2[5/2]_3$
		$-2s^2 2p^5(^2P^0_{3/2})4d^2[7/2]^0_4$
*3601.63	Al III	$3d\,^2D_{5/2} - 4p\,^2P^0_{3/2}$
*3601.93		$3d\,^2D_{3/2} - 4p\,^2P^0_{3/2}$
4332.00	Al II	$3s5s\,^3S_1 - 3s8p\,^3P^0_2$
*4347.24	Al II	$3s4f\,^3F^0_3 - 3s9g\,G$
*4347.32		
*4347.79	Al II	$3s4f\,^3F^0_4 - 3s9g\,G$
*4347.81		
4356.73	Al II	$3s4f\,^1F^0_3 - 3s9g\,G$
4447.81	Al II	$3s4d\,^1D_2 - 3s11p\,^1P^0_1$
4468.94	Al IV	$2s^2 2p^5(^2P^0_{3/2})4s^2[3/2]^0_1$
		$-2s^2 2p^5(^2P^0_{3/2})4p^2[3/2]_1$
*4479.89	Al III	$4f\,^2F^0_{5/2} - 5g\,^2G_{7/2}$
*4479.97		$4f\,^2F^0_{7/2} - 5g\,^2G_{9/2}$
4512.56	Al III	$4p\,^2P^0_{1/2} - 4d\,^2D_{3/2}$
*4528.94	Al III	$4p\,^2P^0_{3/2} - 4d\,^2D_{3/2}$
*4529.19		$4p\,^2P^0_{3/2} - 4d\,^2D_{5/2}$
*4639.33	Al II	$3s4f\,^3F^0_2 - 3s8g\,G$
*4639.38		$3s4f\,^3F^0_2 - 3s8g\,G$
*4639.73		$3s4f\,^3F^0_2 - 3s8g\,G$
*4639.83		$3s4f\,^3F^0_2 - 3s8g\,G$
*4640.36		$3s4f\,^3F^0_4 - 3s8g\,G$
*4640.38		$3s4f\,^3F^0_4 - 3s8g\,G$
4648.61	Al II	$3s4d\,^1D_2 - 3s10p\,^1P^0_1$
*4650.55	Al II	$3s4f\,^1F^0_3 - 3s8g\,G$
*4650.65		$3s4f\,^1F^0_3 - 3s8g\,G$
4654.00	Al IV	$5f[7/2]5g' - 6g[7/2]^0 6h'$
4663.05	Al II	$3p^2\,^1D_2 - 3s4p\,^1P^0_1$
4666.80	Al II	$3s5p\,^1P^0_1 - 3s11s\,^1S_0$
*4701.15	Al III	$4f\,^2F^0_{5/2} - 5d\,^2D_{3/2}$
*4701.41		$4f\,^2F^0_{7/2} - 5d\,^2D_{5/2}$

*Unresolved

Al II

The lifetime of the Al II line at 4663 Å, with upper state $3s4p\,^1P^0_1$ is reported for the first time. The plot of intensity *versus* distance for this line is shown in Figure 2a. The measured decay curve was fitted to a single exponential fit and yielded a lifetime of 11.3 ns. From the available data on transition probabilities of all the known transitions from the upper level $3s4p\,^1P^0_1$ [8], the lifetime of this level was estimated to be 12.3 ns. Since the accuracy of the transition probability data is of the order of 25%, it can be concluded that the lifetime value obtained in the present studies is in close agreement with the theoretically expected value.

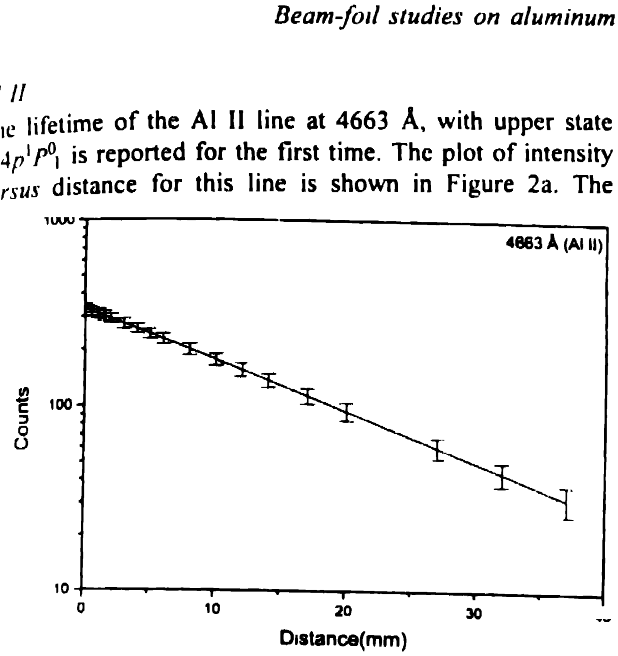

Figure 2(a). Decay curve for the Al II line at 4663 Å

Al III

Four lines belonging to Al III were studied, *viz*, 3601 Å ($2p^5[^2P^0]3p4p\,^2P^0$), 4479 Å ($2p^5[^2P^0]3p5g\,^2G$) 4512 Å ($2p^5[^2P^0]3p4d\,^2D$) and 4529 Å ($2p^5[^2P^0]3p4d\,^2D$). Of these four lines, the line at 4512 Å and the two unresolved lines at 4529 Å are components of a multiplet with the same upper state $4d\,^2D$. As expected, the lifetimes of these two lines are equal within the error limits and agree with the values reported by Andersen *et al* [2].

The two unresolved lines at 4479 Å are also components of a multiplet from upper state $5g\,^2G$. Fitting the measured decay curve with a double exponential fitting program, gave two lifetime components of 4.2 ns and 24.4 ns. The primary lifetime of 4.2 ns is close to the value earlier reported by Weckström *et al* [5]. The plot of the decay curve is shown in Figure 2b.

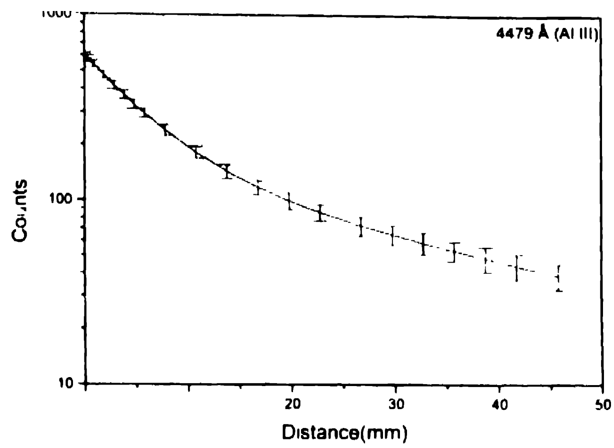

Figure 2(b). Decay curve for the Al III line at 4479 Å

For the doublet at 3601 Å, the decay curve obtained in the present studies, exhibits a single exponential behaviour with a lifetime of 5.7 ns. This value is in agreement with the previously reported value by Weckström *et al* [5] in which the lifetime was extracted using a multi-exponential fit.

Al IV

The lifetime of the Al IV line at 3492 Å with upper state $4d\,^2[7/2^0]_4$ is determined for the first time. The measured decay curve shows a single exponential behaviour with a lifetime of 1.6 ns. Theoretical value of lifetime is not available from literature for comparison. The lifetime studies are summarized in Table 2.

Table 2. List of measured lifetimes

Species	Wavelength (Å)	Upper state	Lifetime (ns) (Present studies)	Lifetime (ns) (Previous studies)
Al II	4663.05	$3s4p\,^1P^0_1$	11.3 ± 0.3	–
Al III	3601.63*	$2p^5[^2P^0]3p4p\,^2P^0_{3/2}$	5.7 ± 0.1	$5 \pm 1_a$
	3601.93*	$2p^5[^2P^0]3p4p\,^2P^0_{3/2}$		
	4479.89*	$2p^5[^2P^0]3p5g\,^2G_{7/2}$	4.2 ± 0.5	$3.2 \pm 0.6_a$
	4479.97*	$2p^5[^2P^0]3p5g\,^2G_{9/2}$		$2.9 \pm 0.2^{\#}_a$
	4512.56	$2p^5[^2P^0]3p4d\,^2D_{3/2}$	5.2 ± 0.6	$4.4 \pm 0.4_b$
	4528.94*	$2p^5[^2P^0]3p4d\,^2D_{3/2}$	4.9 ± 0.9	$4.9 \pm 0.5_a$
	4529.19*	$2p^5[^2P^0]3p4d\,^2D_{5/2}$		$4.4 \pm 0.2^{\#}_a$ $4.4 \pm 0.4_b$
Al IV	3492.23	$2s^2 2p^5[^2P^0_{3/2}]4d\,^2[7/2]^0_4$	1.6 ± 0.1	

\# (cascade corrected); *a*. Weckström *et al* [5], *b* Andersen *et al* [2], * Unresolved

3.2. Excitation function studies .

Excitation function studies were carried out for all lines for which lifetimes were studied. In addition, the line at 4654 Å was investigated in order to confirm its charge state. Excitation functions were plotted by measuring the relative intensities of the lines at several energies, *viz.* 96 KeV, 136 KeV, 176 KeV, 216 KeV, 256 KeV and 296 KeV. The relative intensities were normalized to unity at 296 KeV.

The line at 4654 Å had been assigned to Al IV by Weckström *et al* [5]. However, in the listing by Kaufman *et al* [6], two weak lines at 4653 Å and 4655 Å are listed as belonging to Al II. The source used in these studies was

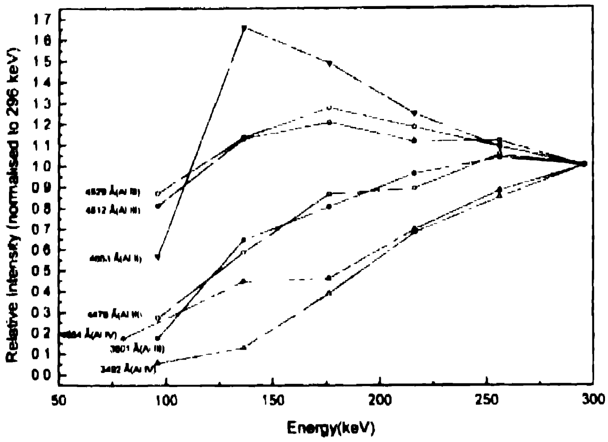

Figure 3. Excitation function plots for Al II, Al III and Al IV lines

an aluminum hollow cathode lamp [9] whereas the source used by Weckström *et al* was beam-foil excitation. The present excitation function studies on this line, confirm that it belongs to Al IV. This is to be expected because in the beam-foil excitation process, higher charge states are expected to be populated as compared to conventional excitation processes. Excitation function of all the seven lines discussed above are plotted together for comparison in Figure 3. It can be seen from this plot that the line at 4654 Å belongs to Al IV.

4. Conclusions

A few intense lines of Al II, Al III and Al IV in the wavelength region 3400–4700 Å were studied by the beam-foil technique. Lifetimes for two of the lines belonging to Al II and Al IV are being reported for the first time. For lines that have been studied previously, mean lifetime values obtained in the present studies are in good agreement with earlier values. Excitation function studies were carried out to confirm the charge states to which the lines belong.

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